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Size effect in micro machining of steel depending on the material state

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Abstract

In machining of steel changes of the surface and boundary layer are induced through mechanical and thermal loads. The controlled generation of these material modifications, which determine the functional properties of components, is still an iterative process based on experience. An enhanced knowledge on the generation of these modifications can only be gained through fundamental investigations. Therefore, this paper investigates mechanical loads in micro machining of 42CrMoS4 by precision turning with focus on the size effect, occurring due to the ratio of undeformed chip thickness to cutting edge radius. Resulting material modifications are examined and discussed regarding the induced loads.

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Keywords: Micro machining ; Surface modification ; Size effect

1. Introduction and target of investigation

The manufacturing of components with desired functional properties is still an iterative process. To generate well-defined properties on the surface and in the surface layer, which fulfill the intended functions, knowledge-based interactions between process-related loads and resulting material properties have to be known. To enable the function-oriented machining of workpieces with different machining processes, these correlations shall be determined to deliver a first approach for a novel knowledge-based material centered view, called Process Signatures [1]. This approach is pursued on the basis of tempered steel 42CrMoS4, which is mainly used in the automotive industry for highly stressed components, e.g. gears and crank shafts or connecting rods. First results for micro turning of steel with geometrically defined cutting edge are presented in this paper. The results contribute to the concept of the Process Signature by investigating small loads and scaling effects.

2. Micro turning of steel

In turning of steel, mechanical and thermal loads prevail, which cause strains and stresses as well as temperature fields in the machined workpiece. As a consequence, state variables like roughness, microstructure, hardness, Young's modulus or residual stresses are changed [2, 3, 4]. The changes of these quantities, which take place on the surface and in the surface layer of a workpiece, are called modifications.

On the one hand the load during machining depends on the material behavior which is determined by the material composition, as well as the heat treatment. Also, the loads depend on the applied manufacturing process and the selected machining parameters. Furthermore, in micro machining processes, size effects can occur, depending on the microstructure and cutting edge geometry [3]. In conventional machining a perfectly sharp cutting edge is assumed. Compared to this, in micro machining the cutting edge is rounded and an effective negative rake angle has a strong impact on the mechanics of the machining process [4]. In metal cutting this is characterized by a non-linear increase of the specific cutting force and energy, dependent on depth of

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cut. The non-linear increase occurs for decreased undeformed chip thickness below a critical chip thickness and is described as a size effect [5, 6].

As a contribution to the Process Signatures this scaling effect, which occurs in the specific cutting force, shall be examined in machining of 42CrMoS4 and in addition, whether such an effect also occurs in the induced material modifications, too.

Therefore, depending on the material initial state and the ratio r_r of undeformed chip thickness *h* to cutting edge radius r_β, the mechanical loads, respectively forces, are investigated by performing precision turning experiments. Additionally, the modifications on the surface and in the surface layer generated by the machining are analysed.

Nomenclature

A	cross-section of undeformed chip (µm²)
b	width of undeformed chip (mm)
f	feed (µm)
F_c	cutting force (N)
F_f	feed force (N)
h	undeformed chip thickness (µm)
k_c	specific cutting force (N mm^{-2})
r_r	ratio of undeformed chip thickness to cutting edge radius (-)
r_β	cutting edge radius (µm)
r_ε	corner radius (µm)
Sa	arithmetic mean height (nm)
v_c	cutting speed (m min^{-1})
v_f	feed velocity (mm min^{-1})
ω	angle of measuring location on workpiece (°)
ϑ	temperature (°C)

3. Experimental work

3.1. Workpiece material

Cylindrical workpiece specimens consisting of 42CrMoS4 (SAE 4140RH, cf. Tab. 1) were investigated. They were made of hot rolled, quenched and tempered steel rods with a diameter of 60 mm. On the front face the specimens have a 1 mm wide ring with an outer diameter of 58 mm. To avoid the induction of loads by clamping, the workpieces were designed with a cylindrical recess (Ø 50 mm). After their fabrication, the samples were heat treated to achieve a well-defined initial state. Three kinds of heat treatments were applied on this steel as indicated in Table 2. Depending on the heat treatment, the workpieces reveal a hardness of 30 HRC, 36 HRC and 42 HRC.

Table 1. Chemical composition of the steel 42CrMoS4 (values in %)

C	Si	Mn	P	S	Cr	Ni	Mo
0.45	0.23	0.78	0.014	0.021	1.12	0.09	0.20

Table 2. Heat treatments applied to 42CrMoS4 steel

	Heat treatment
30 HRC	Austenitisation at 850 °C, then oil quenching and tempering at 685 °C in vacuum
36 HRC	Austenitisation at 850 °C, then oil quenching and tempering at 560 °C in vacuum
42 HRC	Austenitisation at 850 °C, then oil quenching and tempering at 475 °C in vacuum

3.2. Cutting tool

The tools are made of fine grain carbide with a titanium nitride coating. These are 3 mm ± 0.2 mm wide grooving inserts with a cutting edge radius of r_β = 10 µm ± 1.9 µm (measured with a Profiler P-15, KLA Tencor).

3.3. Experimental setup and design

The experiments were performed on a precision lathe (Benzinger Go-Future B2). A multicomponent dynamometer (MiniDyn 9119AA1, Kistler) was attached to the tool revolver with the tool fixed to it. The dynamometer was connected to a multi-channel charge amplifier (5080A with 3 channels, Kistler) with a data acquisition card (NI-USB 6361, National instruments).

Through a free orthogonal cut during turning with uniform engagement conditions, the complexity of the process is reduced (cf. Fig. 1 and Fig. 6). This was ensured by two factors: on one hand, only the ring of the specimen was machined and on the other hand the tool being wider than the workpiece. To analyse the mechanical load as well as modification at different ratios r_r of undeformed chip thickness h to cutting edge radius r_β, the feed in the axial direction f was varied between 3 µm and 90 µm, while the cutting edge radius was kept constant. This results in a ratio r_r between 0.3 and 9. Here, the feed and undeformed chip thicknesses were calculated. To ensure steady process conditions, in each experiment 50 workpiece revolutions were completed. The cutting speed was set to v_c = 80 m min^{-1}. For every single experiment a new tool was used to avoid wear effects. In addition, every parameter set was performed three times.

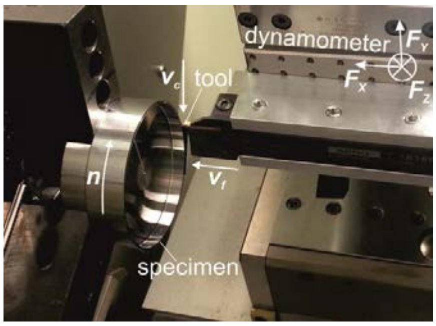

Fig. 1. Experimental setup

4. Results and Discussions

4.1. Acting forces in micro machining

To quantify the mechanical load, the measured forces were evaluated. For the three experiments of each set of parameters the average value and the simple standard deviation were determined. As expected for the orthogonal axial turning, no significant force acts in radial direction.

The cutting force F_c and feed force F_f were plotted as a function of the ratio r_r of undeformed chip thickness to cutting edge radius (cf. Fig. 2). It is noticeable that the cutting force has almost the same values for a hardness of 36 HRC and 42 HRC. In the range of $r_r = 3$ to $r_r = 9$ the force increases linearly from 105 N to 255 N. For a hardness of 30 HRC the cutting force increases in the same range, but the absolute values are about 30 N higher. For $r_r < 3$, the slope is slightly larger. The feed force F_f behaves very similar to the cutting force. Indeed, the absolute values are up to 50 % lower. Moreover, between $r_r = 3$ and $r_r = 9$ the feed force rises linearly again and is significantly higher for a hardness of 30 HRC. The rise in forces for increasing ratios r_r is due to the larger cross-section of undeformed chip. At $r_r = 0.3$, the feed forces as well as the cutting forces lie on a similar level, each.

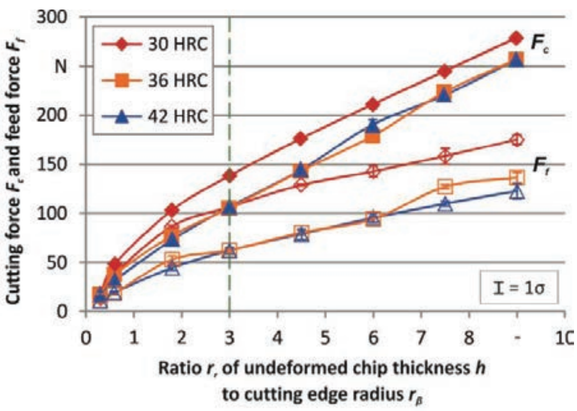

Fig. 2. Cutting force and feed force as a function of the ratio of undeformed chip thickness to cutting edge radius

The specific cutting force k_c is identical to the specific energy for separating a unit volume and was calculated by the following equation:

$$k_C = \frac{F_C}{A} = \frac{F_C}{b \cdot h} \qquad (1)$$

Specific cutting forces for hardnesses of 36 HRC and 42 HRC are almost identical (cf. Fig. 3). In the range of $r_r = 3$ to $r_r = 9$ specific cutting forces decrease slightly linear from approximately 3502 N mm^{-2} to 2839 N mm^{-2}. Again, the forces for 30 HRC are slightly higher. In any case from $r_r = 0.3$ to $r_r = 3$ the decrease is significantly larger. It is striking that for a ratio of 0.3, k_c is around 6000 N mm^{-2} for each hardness. Obviously, the material behavior at 36 HRC and 42 HRC is identical for the parameters studied but not for 30 HRC. Furthermore, at $r_r < 3$ probably the ploughing effect [7] arises.

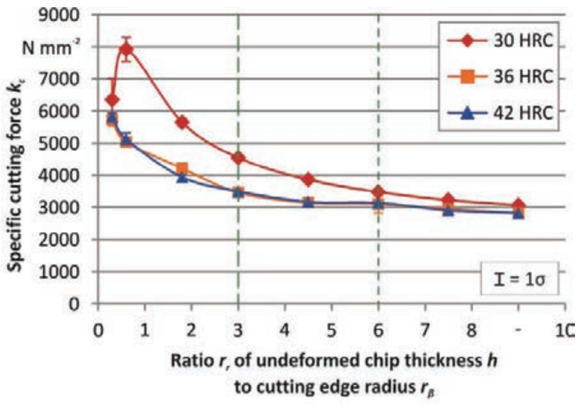

Fig. 3. Specific cutting force as a function of the ratio of undeformed chip thickness to cutting edge radius

Apparently, the material state plays only a subordinate role for the machining process for the very small ratio of 0.3. For a ratio of 0.6, the influence of the material state gets increasingly relevant. For ratios above $r_r = 6$, the different material states (30 HRC, 36 HRC and 42 HRC) behave constantly. The significantly higher forces for 30 HRC than for harder steel can be explained by the fact that more deformation work has to be done before the material is separated. But, as the forces and specific forces are almost identical for 36 HRC and 42 HRC compared to 30 HRC there should be a critical material property or effect which is unknown so far.

4.2. Influence on the surface layer

On selected specimens (30 HRC, 36 HRC and 42 HRC with $r_r = 6.0$ as well as 36 HRC with $r_r = 0.6$) the surface layer was characterised by metallographic analyses. From each of these specimens micrographs were taken (cf. Fig. 4) after polishing and etching with 3 % nitric acid (HNO_3).

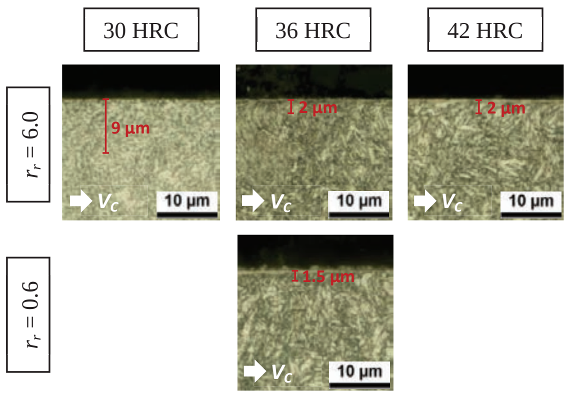

Fig. 4. Micrographs of the microstructure of the surface layer after machining

It can be clearly seen that the bulk material for 36 HRC and 42 HRC appears identical, while the appearance is strongly different for 30 HRC. The latter shows spherical carbides. In all three heat treatment conditions a grain deformation in the cutting direction below the surface can be seen for both ratios investigated. For $r_r = 6$ at 30 HRC the depth of the deformed zone is about 9 µm and at 36 HRC and 42 HRC approximately 2 µm. At 36 HRC and $r_r = 0.6$ the influenced depth is 1.5 µm.

4.3. Influence on the surface

The roughness of the machined workpieces was measured using a white light interferometer (Talysurf CCI HD, Taylor Hobson), adjusted to a cut-off of 0.8 mm. In the best case, a roughness of 202 nm was achieved (cf. Fig. 5). The roughness *Sa* fluctuates between 202 nm and 410 nm, for larger ratios in the range of $r_r = 3$ to $r_r = 9$. Here, for 42 HRC, the most constant values are measured around 280 nm. Overall, the values have large standard deviations. Again, it is noticeable, that at a ratio of 0.3, the roughness is around the same value: $Sa \approx 560$ nm, for each hardness.

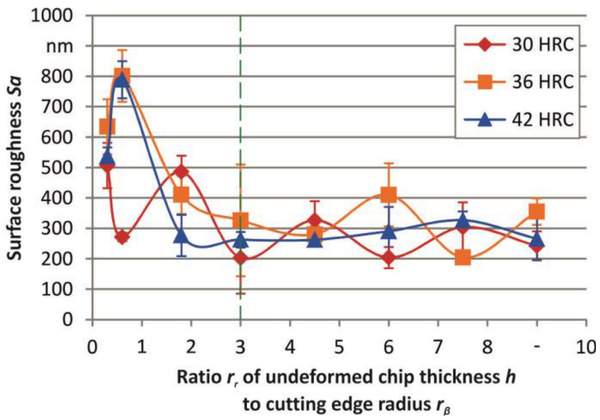

Fig. 5. Surface roughness as a function of the ratio of undeformed chip thickness to cutting edge radius

The roughness was measured on each workpiece at four angular positions ω (cf. Fig. 6). Considering the four roughness measurements of the same specimen, there are significant differences between the individual measurements (cf. Tab. 3). After completion of the machining, at 0° and 270° roughness was significantly better than at the other two positions. In white light interferometric pictures at 90° and 180° peaks are visible, generated by cutting edge chipping, which obviously, have been removed at 90° and 180°, as the tool moved out of engagement, resulting in a better roughness. Apparently, there was a “spark-out” as it otherwise occurs during grinding. This may explain the large standard deviations of the roughness values. But this does not occur in all tests in the same way.

ω	*Sa* in nm
0°	334.8
90°	455.0
180°	438.1
270°	347.6

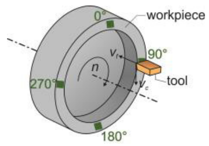

Fig. 6. Roughness measurements of the same specimen (36 HRC; $r_r = 6.0$) at four locations (ω)

5. Conclusions

This study examines the mechanical load and modifications depending on the heat treatment with respect to the ratio of undeformed chip thickness to the cutting edge radius.

- The ratio of undeformed chip thickness to the cutting edge radius has a significant influence on the specific cutting force for ratios < 3 (with respect to heat treatments and parameters which were investigated).
- Depending on the heat treatment, the size effect in the form of an increase in the specific cutting force as well as the depth of the deformed zone show partially strong differences.
- For higher mechanical loads the depth of the modified surface layer is larger.
- Due to the unspecific engagement conditions with a conventional machine tool, when the tool moves out of engagement, and resulting rubbing effect, statements about a size effect in terms of the modification are only possible with limitations. For this purpose, an abrupt interruption of the cutting shall be realised in future.
- Regarding the roughness of 36 HRC and 42 HRC, a scaling effect for $r_r < 1$ is shown. To analyze the effective mechanisms, further studies, including the surface layer, need to be done, both empirical investigations and numerical simulation.

Acknowledgements

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